Con-X IGM Studies (WHIM)

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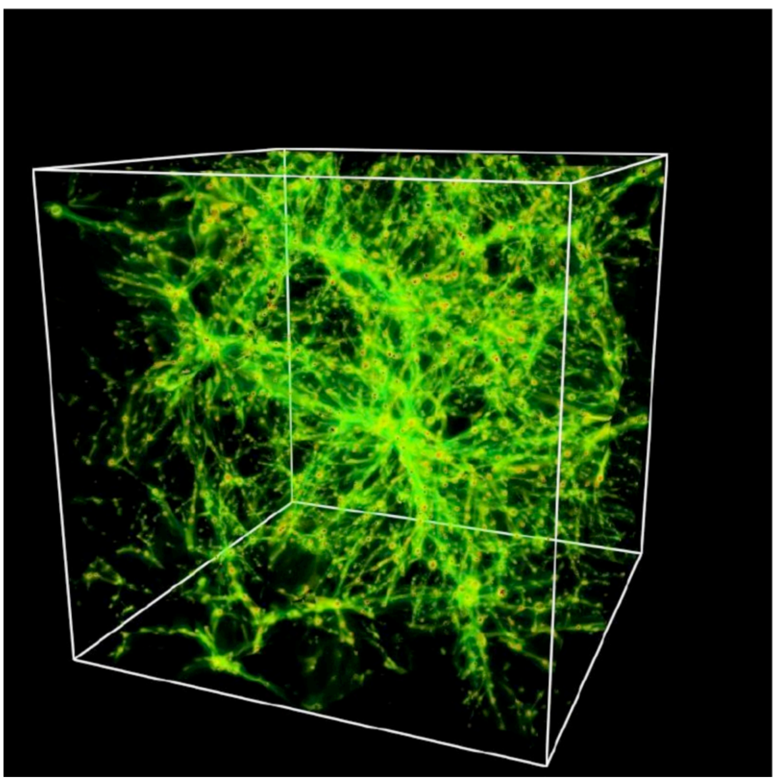
One of the major astronomical puzzles is the location of the "missing baryons". Where is the 90% of ordinary matter not contained in luminous, collapsed form (galaxies, groups, and clusters)? At high redshift, much of this matter resides in the intergalactic medium (IGM). Does intergalactic space provide a similar gaseous reservoir at low redshift ($z < 0.5$)? If so, what are the implications of this gas for late-time infall onto galaxies and for the chemical evolution of their disks and halos?

Theoretical simulations (e.g., Cen & Ostriker 1999; Dave et al. 2001) of large-scale structure and cosmological hydrodynamics suggest that the IGM is a hierarchically structured, filamentary network (the "cosmic web") shaped by processes of gravitational collapse, shock-heating from galactic outflows, and photoionization by QSOs. The cosmic web therefore provides a rare opportunity to observe cosmological processes at work: gravitational instability of dark matter, baryonic infall and shocks, and radiative, mechanical, and chemical feedback from galaxy formation.



Studying the low-redshift IGM in the UV and X-ray wavebands is particularly important, since astronomers are then able to conduct sensitive galaxy surveys (Sloan, 2DF, etc.) that probe the connections between IGM and galaxies down to sub-L* luminosity (Bowen, Pettini, & Blades 2002; Stocke, Shull, & Penton 2005). Both UV and X-ray spectroscopic studies of the cosmic web at $z < 0.2$ suggest that the IGM may still contain up to 80% of all baryons, spread throughout a diffuse, multiphase medium at temperatures ranging from 10^4 K up to 10^7 K. This large-scale gaseous structure has come to be termed the "Cosmic Web".

The IGM clearly has cosmological significance for the assembly of galaxies, feedback from star formation, and chemical history of galaxies. Thus, it is worth examining in some detail the technical requirements for making a major improvement in X-ray absorption-line spectroscopy of the hot IGM and galactic halos. This improved capability will come from increased throughput (to at least 2000 cm^2) and from better spectral resolution (factor of 2-4) over Chandra. Such capabilities would revolutionize X-ray IGM science, and could provide access to several observable AGN targets behind galaxy halos. It would allow astronomers to probe ~100 AGN sightlines in a census of "missing baryons" in the warm-hot IGM (WHIM), using X-ray absorption lines of O VII, O VIII, N VI, N VII, C VI, Ne IX, etc. (Nicastro et al. 2005a,b).

Detecting and measuring the Cosmic Web is therefore a worthy challenge, requiring high-throughput spectrographs aboard both X-ray and ultraviolet telescopes. The warm phase (10^4 K) of the IGM has been detected by the Hubble Lyman-alpha survey (Penton, Shull, & Stocke 2004). Approximately 30% (+/- 4%) of the baryons reside in this photoionized gas, and another 5-10% are in collapsed halos. Some 5-10% have been inferred from UV resonance lines of O VI, a sensitive tracer of gas at 10^5 - 10^6 K (Tripp, Savage, & Jenkins 2000; Danforth & Shull 2005). This leaves 40-50% unaccounted for, perhaps residing in the theoretically predicted gas at $T > 10^6$ K. These hot baryons are only detectable in X-ray absorption from high ions of trace heavy elements.

Astronomers can use these X-ray absorbers to study the chemical flows of matter -- from supernovae, to the galactic interstellar medium, and finally out into intergalactic space via galactic winds. These investigations will require far more capable spectrographs than available on Chandra or XMM-Newton, a capability characterized by increases in both effective spectroscopic collecting area (A_{eff}) and higher spectral resolution, $R = (E/\Delta)$ at 0.3-1.0 keV, where Delta E is the FWHM of the resolution element.

With Chandra and XMM-Newton, X-ray astronomers have now found the first hints of this hot gas in the vicinity of the Milky Way and Local Group through $z = 0$ absorption lines in the spectra of background AGN (Nicastro et al. 2002; Fang et al. 2003; McKernan et al. 2004). Good tracers of million-degree Galactic halo gas are the X-ray resonance lines of O VII (21.6019 A) and O VIII (18.9689 A), with additional nucleosynthetic information available in other lines such as N VI (28.787 A), N VII (24.782 A), Ne IX (13.337 A), and C VI (33.736 A). These lines should appear in external galaxies as well, given a suitable background target.

Even more exciting cosmologically are the redshifted absorption lines from the "WHIM" -- the Warm-Hot Intergalactic Medium. The first claimed detections of million-degree WHIM came from Chandra observations of two low-redshift O VII absorbers ($z = 0.011$ and $z = 0.027$) toward the X-ray flaring blazar Mrk 421 (Nicastro et al. 2005a,b). These absorption features are weak (3-4 sigma detections), and the O VII statistics are uncertain (two possible absorbers over a redshift path length of only Delta z = 0.03). These detections are consistent with a large reservoir of WHIM at $\sim 10^6$ K, containing a significant fraction of the missing baryons, assuming a fiducial O/H metallicity of 10% solar. This metallicity needs verification by other means; see Danforth & Shull (2005) for an approximate determination of O/H at 9% solar from O VI/H I statistics.

The future of X-ray spectroscopy of the WHIM is bright. NASA is studying a new generation X-ray satellite (Constellation-X) with spectrographs having increased throughput and resolution at 0.3-1.0 keV. Because the current Chandra/LETG WHIM detections are marginal, with 3-4 sigma significance at resolution (FWHM) of 750 km/s, the Con-X spectrographs will need to have much better spectroscopic throughput and resolution. A critical tradeoff is between R and A_{eff}, to maximize the number of AGN sightlines that can be surveyed down to critical column density limits in O VII and other ions. Recent simulations (Fang, Bryan, & Canizares 2002; Chen et al. 2003) find a line frequency of O VII absorbers between dN/dz = 1-10 at low redshift, for fiducial column densities N(O VII) > 10^{15} cm^{-2}. Con-X should set a goal of detecting at least 30 and preferably 100 WHIM absorbers, toward ~100 AGN over total redshift pathlength Delta z > 30. This hot-IGM survey would then match the current standard (HST/STIS and FUSE) and future goals of UV spectroscopy. FUSE and HST/STIS have detected over 80 O VI absorbers; the Cosmic Origins Spectrograph (HST/COS) or a future Cosmic Web Probe will find many more (weaker) O VI absorbers, which are extremely important as "signposts" of locations to search for shocked O VII and other X-ray lines.

In view of the potentially large baryon reservoir in the hot IGM, X-ray spectroscopy of the WHIM should be brought up to at least the current level of O VI spectroscopy with FUSE. Detections of weak O VII and other X-ray absorbers can be achieved, both by increasing A_{eff} to at least 2000 cm^2 (at 0.3-1.0 keV) and by obtaining a better match between the velocity (FWHM) resolution element (Delta V = c/R) and the expected equivalent widths (W_v) and thermal line widths of the WHIM absorbers. The minimum detectable column density of a given ion scales as:

N_{min} ~ (line strength)(Delta-V)_FWHM / (S/N)

where the intrinsic line strength is given by the product, (f lambda), of oscillator strength and wavelength. The velocity resolution and signal-to-noise ratio (S/N) are determined by properties of the instrument and the duration of the observation. For fixed A_{eff} on bright targets, (S/N) is proportional to $(A_{eff})^{1/2}$, and N_{min} scales as the square root of the resolution element, $(\text{Delta-V})^{1/2}$. For this reason, it is important to understand the instrumental and cost trade-offs between effective area and spectral resolution.

Typical X-ray absorption lines (O VII, O VIII) are intrinsically 10-40 times weaker than their UV counterparts (O VI, Ne VIII). As a result, current UV spectrographs with 10-20 km/s resolution (HST/STIS and FUSE) can detect O VI (1032 A) down to column densities N(O VI) = 10^{13} cm^{-2}, while the claimed Chandra detections of the WHIM have N(O VII) = 10^{15} cm^{-2}, a factor of 100 higher. Although QSO photon fluxes in the soft X-ray are much lower than in the UV, one can partially compensate for this by longer duration exposures and by noting that hydrogenic and helium-like ions (O VIII and O VII) typically have 4-5 times higher ionization fractions than the lithium-like ions, O VI and Ne VIII. In general, one must find at least a factor of 40 improvement in X-ray spectroscopic capability to make WHIM spectroscopy a powerful IGM diagnostic tool.

Several considerations suggest that a high-throughput X-ray spectrograph with at least 200 km/s resolution (R = 1500) would provide a substantial increase in WHIM detectability. First, the claimed Chandra WHIM detections show weak O VII absorption features, with 2-3 mA equivalent widths (W_v = 30-40 km/s). To detect these lines with Chandra resolution (750 km/s) requires extremely high signal-to-noise, S/N = 75 for a 4-sigma detection. For example, the claimed Mrk 421 detections of O VII (Nicastro et al. 2005) had over 5000 counts per 750 km/s resolution element near 20 A, acquired in two 100 ksec exposures when the source flared to 40-60 mCrab flux (1 mCrab is 2×10^{-11} erg cm^{-2} s^{-1} in the 0.5-2 keV band). If the velocity resolution element were reduced to 200 km/s, the abundant weak O VII absorbers could then be detected at S/N = 20, or only 400 cts per resolution element above background -- with a reduced exposure time. At the typical (1-2 mCrab) quiescent X-ray fluxes of low-z AGN, a 100 ksec exposure (with A_{eff} = 2000 cm^2 and R = 1500) will produce between 200-400 counts per resolution element at E = 500 eV. Thus, Con X could easily survey over 100 AGN sightlines and provide statistically significant measures and maps of the WHIM. The brightest (X-ray flaring) AGN would yield very good spectra, and the WHIM surveys could be pushed to somewhat higher redshifts for the rare, brightest sources.

A second reason for designing to R > 1500 (200 km/s) is to resolve hot-IGM lines. The expected O VII and O VIII thermal line widths are (Delta-V) = (53.5 km/s)$(T_6)^{1/2}$ (FWHM) at temperatures of (10^6 K) T_6. Resolving thermal widths would therefore require R = 5600 $(T_6)^{-1/2}$. However, the lines are also broadened by IGM shock dynamics and shear flows. One gauge of these effects comes from the observed kinematics of the UV absorbers (H I and O VI) studied with HST/STIS and FUSE. These absorbers show two-point correlations in velocity at separations (Delta-V) < 200 km/s (Penton et al. 2004). Much of this correlation comes from H I line pairs, which are also seen in O VI absorption lines separated by 150-250 km/s (Shull et al. 2003; Tumlinson et al. 2005). Comparative UV/X-ray absorption studies of H I, O VI, and O VIII using FUSE, HST, and Chandra (Fang et al. 2002; Shull et al. 2003) demonstrate that one needs resolution of 100-200 km/s (R = 1500-3000) to identify and separate kinematically the IGM absorbers and relate them to the nearest galaxies at distances of 0.2 - 1 Mpc. Such velocity resolution would also allow one to identify the absorbers with possible galaxy halos and infalling baryonic matter in small groups. These observations can also address issues of chemical feedback and the extent of heavy-element transport from galaxy outflows into the IGM.

Thus, one can justify resolutions ranging from R = 1500 for IGM absorber-galaxy kinematics up to R = 5000 for line profile studies. These capabilities would allow Con-X spectra to be tied to the current state of moderate-resolution UV spectra (HST, FUSE) of H I, O VI, C III, C IV, and other metal ions. They would also allow astronomers to use Con-X as a powerful tool for studies of the missing baryons and large-scale structure in the hot, shocked IGM. A resolution R = 1500 provides an achievable compromise between resolution, throughput, and cost, and it should provide sufficient line sensitivity and separability to resolve the expected dynamic structures in the WHIM. We therefore summarize the MINIMUM scientific requirements for "Hot IGM" studies by Con-X:

Resolution	R > 1500 (Delta V = 200 km/s)
Wavelength accuracy	20% of this value, or 40 km/s
Throughput	$A_{eff} > 2000$ cm^2

With a 40-fold increase in spectroscopic capability over Chandra, Con-X will be able to study the hot gas behind the extended halos of selected galaxies, using background AGN as targets.

*** Ann: Refer here to Strickland photo of halo gas in external spiral galaxies ***

Another experiment that should be pursued is to follow the evolution of the shock-heated WHIM backward in time, out to redshift z = 0.5. At these redshifts, cosmological simulations predict a significant diminution in the baryon fraction of million-degree (WHIM) plasma, owing to a reduced rate of shock heating from gravitational structure formation (Dave et al. 2001). The slow chemical evolution of the IGM may also play a role, as the high-z IGM is expected to have lower metallicities arising from galaxy outflows and tidal stripping (Gnedin & Ostriker 1997).

The critical spectral band for hot-IGM studies is 10-40 A, where X-ray detectors should allow clean, high-quality spectra to be obtained away from the carbon K-edge. Using the predicted strongest WHIM absorption features and the 40 A cutoff, Con-X should be able to measure absorbers out to redshifts $z_{max} = 0.61$ (N VII), $z_{max} = 0.85$ (O VII), $z_{max} = 1.10$ (O VIII), and $z_{max} = 2.0$ (Ne IX) as long as a few X-ray bright AGN can be found. The brightest AGN at z = 0.1-1.0 have quiescent soft X-ray fluxes of 1-2 mCrab (2×10^{-11} erg cm^{-2} s^{-1} at 0.5-2 keV). Most AGN are fainter; a recent ROSAT survey of Sloan Survey quasars (Shen et al. 2005) found a broad distribution of 0.5-2.0 keV AGN fluxes ranging from 2×10^{-13} to 2×10^{-12} erg cm^{-2} s^{-1}, with a few at 10^{-11} flux. The claimed WHIM detection (Nicastro et al. 2005) by Chandra toward Mrk 421 (z = 0.03) came when it flared to 10^{-9} erg cm^{-2} s^{-1}.

This cosmological experiment will be time-intensive, probably requiring exposures of 100 ksec for typical AGN (1-2 mCrab) and few up to 500 ksec. It may therefore benefit from a strategy of selecting X-ray variable AGN (blazars) and waiting for them to flare. However, the potential rewards of this program are great, particularly when the X-ray diagnostics of the hottest WHIM plasma are combined with similarly increased capability for UV spectroscopy in lines of H I, O VI, C III, C IV, etc. The proposed Con-X mission will perform the hot-IGM survey quite well, and should obtain very good spectra on the brightest targets. The scientific results from a XEUS mission, with $A_{eff} = 40{,}000\ cm^2$ and R = 5000, would produce powerful physical tests of the WHIM and its metallicity evolution.

References

Bowen, D.V., Pettini, M., & Blades, J.C. 2002, ApJ, 580, L69

Cen, R. & Ostriker, J.P. 1999, ApJ, 519, L109

Chen, X., Weinberg, D.H., Katz, N., & Dave, R. 2003, ApJ, 594, 42

Danforth, C. & Shull, J.M. 2005, ApJ, 625, in press (May 20), astro-ph/0501054

Dave, R. et al. 2001, ApJ, 552, 473

Fang, T., Bryan, G., & Canizares, C. 2002, ApJ, 564, 605

Fang, T., et al. 2002, ApJ, 572, L127

Fang, T., Sembach, K., & Canizares, C. 2003, ApJ, 586, L49

Gnedin, N.Y., & Ostriker, J.P. 1997, ApJ, 486, 581

McKernan et al. 2004, ApJ, 617, 232

Nicastro, F., et al. 2002, ApJ, 573, 157

Nicastro, F., et al. 2005a, Nature, 433, 495

Nicastro, F., et al. 2005b, ApJ, in press

Penton, S.V., Stocke, J.T., & Shull, J.M. 2004, ApJS, 152, 29

Shen, S., White, S.D.M., Mo, H.J., Voges, W., Kauffman, G., & Tremonti, C. 2005, MNRAS, preprint.

Shull, J.M., Tumlinson, J., & Giroux, M.L. 2003, ApJ, 594, L107

Stocke, J.T., Shull, J.M., & Penton, S.V. 2005, to appear in Proceedings of May 2004 Symposium, Space Telescope Science Institute, "From Planets to Cosmology".

Tripp, T., Savage, B.D., & Jenkins, E.B. 2000, ApJ, 534, L1

Tumlinson, J., Shull, J.M., Giroux, M.L., & Stocke, J.T. 2005, ApJ, 620, 95